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EMPIRICAL ANALYSIS OF PROJECTILE PENETRATION IN ROCK

by

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Data from 23 penetration tests have been analyzed empirically to produce a nondimensional equation for projectile penetration in rock:

$$\frac{\rho Z}{M/A} = 0.2\ V \sqrt{\frac{\rho}{Y}} \left(\frac{100}{RQD}\right)^{0.8}$$

where

ρ = mass density of the rock (Continued)

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20. ABSTRACT (Continued).

Z = depth of penetration

M = projectile mass

A = projectile cross-sectional area

V = impact velocity

Y = unconfined compressive strength of the rock

RQD = Rock Quality Designation

The data base consists of normal impact and penetration data for rock (11 tests) and for concrete (12 tests, used as a baseline). The test projectiles had ogive noses, diameters between 76 and 203 mm, masses between 5.9 and 613 kg, and impact velocities from 251 to 809 m/s. The rock penetration equation is given in dimensional form and also in nomogram form. Calculated results are compared with badly scattered bomb penetration data for granite and sandstone. The equation gives about the same result as a least-squares linear fit to the data.

Preface

The investigation reported herein was sponsored by the Defense Nuclear Agency (DNA) under Subtask Y99QAXSB211, "Penetration," Work Unit 14, "Technical Penetration Developments." The development of a rock penetration nomogram, which was the end product of the investigation, was suggested by MAJ Todd D. Strong, CE, who was the DNA Project Officer at the beginning of this work unit.

The study was conducted by personnel of the Soils and Pavements Laboratory (S&PL), U. S. Army Engineer Waterways Experiment Station (WES), during July-October 1976 under the general supervision of Messrs. J. P. Sale and R. G. Ahlvin, Chief and Assistant Chief, respectively. Mr. R. S. Bernard developed the penetration formula with the technical guidance of Drs. P. F. Hadala and B. Rohani under the direct supervision of Dr. J. G. Jackson, Chief of the Soil Dynamics Division, S&PL. Mr. Bernard also prepared the report.

COL J. L. Cannon, CE, was Commander and Director of WES during the investigation and at the time of preparation of this report. Mr. F. R. Brown was Technical Director.

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EMPIRICAL ANALYSIS OF PROJECTILE PENETRATION IN ROCK

Introduction

The design and deployment of earth penetrating weapons requires simple, reliable techniques for predicting their performance in soil and rock targets. Bernard and Creighton (Reference 1) have developed a time-sharing computer code (PENCO) that analyzes projectile motion within layered earth targets. Although the theory used in PENCO is fairly simple, the calculations are too cumbersome to be performed by hand. It is therefore desirable to have an even simpler prediction technique that does not require a computer.

Young's equation (Reference 2) has proved to be the simplest and most effective empirical formula for soil penetration. This equation uses an empirical penetrability index, which varies from target to target and which must be determined from previous penetration data. Soil penetration has been extensively investigated in recent years, and the information already on record is adequate for generating reasonable predictions in many types of soil.

Young's equation has occasionally been used to correlate rock penetration data, even though the equation itself was derived from soil penetration data. Since it has never been shown that the scaling relations for soil are the same as those for rock, there is clearly a need for an equation based on penetration data for rock in situ. The development of a penetration formula specifically for rock is summarized in the following paragraphs.

Empirical Rock Penetration Equation

The first step in an empirical analysis is to quantify the effects of those variables that can be specified most accurately. For penetration, these variables are the projectile mass (M), diameter (D), nose

shape (CRH),[1] and impact velocity (V). Once the relation between penetration and projectile parameters is understood, the analysis can proceed to the effects of variables that are less accurately specified (i.e. the target parameters).

Experimental data for concrete (Reference 3) indicate that the final penetration depth (Z) is roughly proportional to the projectile mass and impact velocity and inversely proportional to the square of the projectile diameter. Most rocks are hard and brittle (like concrete), so it is assumed that the same trends apply for intact (unjointed) rock. Of course, the degree of penetrability will change from target to target.

Penetrability is probably related to a number of target variables, such as density, shear strength, tensile strength, bulk and shear moduli, and other properties. Unfortunately, it is rare to find penetration data for rock sites where all these quantities were known with consistent accuracy, even when the rock was in an intact condition. It is therefore assumed that the penetrability of intact rock depends only on the mass density (ρ) and the unconfined compressive strength (Y), which are the two properties most often measured.

Natural rock deposits often contain joints and fractures, so that the unconfined compressive strength of intact core specimens may fail to characterize the rock as a whole. Deere (Reference 4) has proposed the Rock Quality Designation (RQD) as an index for the degree of fracturing of the rock in situ at a given site. The value of the RQD is determined by a modified core logging procedure:

> All solid pieces of core that are 10 cm long or longer are added up, and this length is called the modified core recovery. The modified core recovery is divided by the total length of core run, and the quotient multiplied by 100 percent is the value of the RQD.

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[1] $\text{CRH} = \dfrac{\text{ogive nose radius}}{\text{projectile diameter}}$

The RQD has previously been shown to be related to other qualitative rock descriptors, such as fracture frequency. Now it seems also to be an index of penetrability.

A number of dimensionless equations can be constructed that relate the projectile and target variables. One of these has the form

$$\frac{\rho Z}{M/A} = f(V\sqrt{\rho/Y}\ ,\ RQD\ ,\ CRH) \tag{1}$$

All quantities in Equation 1 <u>must</u> be expressed in compatible units.[3] The left-hand side represents a dimensionless penetration depth, and the first group ($V\sqrt{\rho/Y}$) on the right-hand side represents a dimensionless impact velocity. Aside from the introduction of the RQD, Equation 1 contains natural dimensionless groups involving the mass, velocity, diameter, and geometry of the projectile, as well as the intact strength and density of the target.

Physical property data are incomplete for the targets in most of the rock penetration tests on record. However, target descriptions adequate for the present analysis do exist for 11 rock penetration tests conducted by Sandia Laboratories under ERDA or DNA[4] sponsorship (References 5-9). Figure 1 shows these data plotted with concrete penetration data[5] taken from Reference 3. Table 1 enumerates the 23 individual test results, and Table 2 gives the projectile and target parameters. The combined data were used to obtain a penetration equation of the same general form as Equation 1.

The penetration data for concrete (Canfield and Clator, Reference 3) and for welded tuff (Sandia/DNA tests, Reference 5) constitute the baseline for intact rock (RQD ≈ 100) in Figure 1. The other data

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[3] For example, ρ could be expressed in g/cm^3, Z and D in cm, M in grams, A in cm^2, V in cm/s, and Y in dynes/cm^2.

[4] ERDA is an acronym for <u>E</u>nergy <u>R</u>esearch and <u>D</u>evelopment <u>A</u>gency, and DNA, for <u>D</u>efense <u>N</u>uclear <u>A</u>gency.

[5] The rock penetration data are, by themselves, a bit too scattered for comfort. The addition of the concrete data fills in the loose pattern of the rock data, facilitating a reasonable correlation of all the test results.

(for RQD < 100) are documented in References 5 and 6. The properties for the concrete, the welded tuff, and the 82-RQD sandstone are discussed in References 3, 7, and 9, respectively. The properties of the remaining targets are given in Reference 9.

Various attempts were made to correlate the dimensionless parameters that appear in Equation 1. Figure 1 shows the most successful normalization of the data. The equation for the dashed line in Figure 1 is

$$\frac{\rho Z}{M/A} = 0.2\ V\sqrt{\frac{\rho}{Y}}\left(\frac{100}{RQD}\right)^{0.8} \tag{2}$$

where $A = \frac{\pi}{4}D^2$ is the projectile cross-sectional area.

The error bars in the figure reflect the relative uncertainty in the value of the target strength. There are many test results on record that could not be used in the formulation of Equation 2, due to a lack of descriptive data for the targets. However, the points in Figure 1 represent tests for which the target density, strength, and RQD were all known within reasonable bounds.

The available data did not show a significant increase in penetration depth as CRH increased from 1.5 to 9.25, so the nose shape variable was dropped from the analysis. However, the equation is <u>not</u> considered valid for blunt-nosed projectiles, since no blunt projectile data were used in its formulation.

Expressed in metric units, Equation 2 becomes

$$Z = 25.4\ \frac{M}{D^2}\ \frac{V}{\sqrt{\rho Y}}\left(\frac{100}{RQD}\right)^{0.8} \tag{3}$$

where

- Z = final penetration depth, cm
- M = projectile mass, kg
- D = projectile diameter, cm
- V = impact velocity, m/s
- ρ = target bulk density, g/cm^3
- Y = unconfined compressive strength of the intact rock, bars

RQD = Rock Quality Designation, pct

Equation 3 is expressed as a nomogram in Figure 2, which includes a sample calculation using the nomogram.

Limitations

Although concrete data were used in the development of Equation 2, this expression is not intended as a concrete penetration formula. The concrete data were introduced only to help establish the baseline for intact rock. There are several equations already documented for concrete (e.g. Reference 10), which produce better results in concrete than Equation 2. For rock targets, the penetration data are more scattered (and the target parameters more uncertain) than for concrete targets. It then follows that a rock penetration equation must be inherently less accurate than a concrete penetration equation.

Due to the limited penetration data base, the restrictions on Equation 2 are as follows:

1. At best, the accuracy of prediction is ± 20 percent.
2. The equation is valid only when the calculated depth is greater than three projectile diameters.
3. For nearly intact rock (RQD > 90), the equation appears to be applicable for projectiles from 3 to 30 cm in diameter.
4. For rock with RQD < 90, the equation has not been verified for projectiles outside the 10- to 30-cm-diam range.
5. If RQD < 20, the equation should not be used at all.
6. The effect of nose shape seems to be weak, but the equation is not recommended for blunt or near-blunt (CRH < 1.5) projectiles.
7. The equation is not valid if the projectile "mushrooms" or breaks up.
8. The equation is not valid if the projectile tumbles, or if the penetration path is sharply curved.

If possible, the target strength should be determined from static unconfined compression tests of intact rock samples, and the values used for Y and RQD should correspond to the same borehole.

Appendix A contains information that can be used to make rough

estimates of ρ , Y and RQD in those cases where only a word description of the target is available. However, in such cases only very rough estimates of penetration depth can be made. For example, an uncertainty of ± 50 percent in Y compounded with ± 20 percent in RQD will produce an error band of ± 70 percent in the predicted depth. If there exist <u>any</u> previous penetration data for the site in question, these data should be used as bench marks for checking the results obtained from Equation 2 and (indirectly) the target parameters used therein.

Comparison with Bomb Penetration Data

Reference 11 (EM 1110-345-434) contains a rock penetration equation based on data obtained by Livingston and Smith (Reference 12). In these tests, inert 1600-pound AP, 2000-pound SAP, and 25,000-pound SAP bombs were dropped on sandstone and weathered granite targets at impact velocities of 256-381 m/s. The bombs struck the targets at angles of 15-30 degrees from the vertical, and the penetration paths were all somewhat curved. No RQD data are available for these tests. However, recorded descriptions (and a few pictures of core boxes) suggest an RQD of 20-40 percent for the granite site and 50-70 percent for the sandstone site. Table 3 gives the ranges of strength and density for the two target areas, and Table 4 presents the bomb characteristics.

The bomb penetration depths were equated with the <u>total</u> (curved) path lengths, and the data were nondimensionalized (Figure 3) by the method used in Figure 1. The horizontal error bars in Figure 3 were obtained by using the lower limits of Y and RQD to calculate the upper bound of the abscissa, and vice versa. The average density was used in each case, and the median values of the abscissa are shown plotted with circles and triangles. The data are badly scattered vertically (<u>not</u> due to the nondimensionalization), though Equation 2 is approximately the same as a least-squares linear fit drawn through the origin. The (vertical) standard deviation of the data is ± 33 percent. This comparison demonstrates both the experimental uncertainty and the computational error that are often met in practice.

Summary

Equation 2 is a nondimensional empirical formula[6] for calculating projectile penetration in massive rock deposits. It is expressed in terms of standard engineering properties, which can be determined without conducting full-scale penetration tests. The equation was derived from a limited data base, and its range of applicability should be reassessed as more penetration data become available. However, in the absence of a better prediction technique, Equation 2 is suitable for making reasonable estimates of final penetration depth.

Recommendation

Equation 2 is apparently an improvement over the rock penetration equation given in Reference 11, since (1) it fits the original data on which that equation was based; (2) it fits more recent data; (3) it is dimensionally homogeneous; and (4) the rock penetrability is defined in terms of measurable parameters instead of empirical coefficients. Thus, it is recommended that the rock penetration equation (in any or all of its dimensional, nondimensional, or nomographic forms) be included in the next revisions of References 10 and 11.

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[6] Equation 3 gives the dimensional form in metric units.

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TABLE 1 PENETRATION DATA

Test Results	Target	Impact Velocity m/s	Penetration Depth cm
Canfield and Clator	Concrete	306	20.3
"	"	312	22.9
"	"	381	25.4
"	"	453	36.9
"	"	541	41.9
"	"	602	59.7
"	"	616	49.5
"	"	709	66.0
"	"	716	61.0
"	"	741	69.8
"	"	773	73.7
"	"	809	74.9
Sandia/DNA	Welded Tuff	372	222.0
"	"	411	259.0
"	"	475	360.0
"	"	501	335.0
"	"	503	335.0
Sandia/DNA	Sandstone	444	357.0
"	"	459	372.0
Sandia No. 120-77	Welded Agglomerate	325	396.0
Sandia No. 120-112	Sandstone	251	311.0
Sandia No. 120-103	Sandstone	268	305.0[a]
Sandia No. 120-106	Granite	262	381.0

[a] In this test the sandstone was covered by 76 cm of soil, so the total depth of penetration is 381 cm. However, the penetration resistance of the soil is negligible compared with that of the rock.

TABLE 2 PROJECTILE AND TARGET PARAMETERS

Test Results	Projectile Mass kg	Projectile Diameter cm	Projectile Nose Caliber Radius[a]	Target	Target Strength bars	Target Density g/cm^3	Target RQD %
Canfield and Clator	5.9	7.62	1.50	Concrete	345 ± 5%	2.42	100
Sandia/DNA	208.0[b]	16.51	6.00	Welded Tuff	600 ± 15%	1.95	100
Sandia/DNA	208.0[b]	16.51	6.00	Sandstone	234 ± 30%	2.08	82
Sandia No. 120-77	390.0	22.86	9.25	Welded Agglomerate	275 ± 20%	1.92	60
Sandia No. 120-112	1166.0	25.88	9.25	Sandstone	489 ± 10%	2.12	37
Sandia No. 120-103	613.0	20.32	9.25	Sandstone	408 ± 5%	2.14	32
Sandia No. 120-106	613.0	20.32	9.25	Granite	462 ± 15%	2.62	32

a The nose shape is a tangent ogive in each case.

b The actual projectile mass is 181 kg, but a 53-kg sabot is attached to the projectile base at impact. It is assumed that the projectile and sabot separate about halfway through the penetration process. This makes the "average" projectile mass about 208 kg.

TABLE 3 TARGET PARAMETERS FOR BOMB PENETRATION

Material	Density g/cm^3	Strength bars	Estimated RQD %
Sandstone	2.13 ± 0.01[a]	346 ± 112	50-70
Weathered Granite	2.73 ± 0.02	630 ± 139	20-40

[a] Average ± standard deviation.

TABLE 4 BOMB PARAMETERS

Type of Bomb	Mass, kg	Diameter, cm
1,600-lb AP	748 ± 3	35.56
2,000-lb SAP	936 ± 5	47.65
25,000-lb SAP	$11,449 \pm 11$	58.72

LEGEND

SYMBOL	TARGET	RQD %	STRENGTH BARS	SOURCE OF DATA
○	CONCRETE	100	345	CANFIELD & CLATOR
△	WELDED TUFF	100	600	SANDIA/DNA TESTS
□	SANDSTONE	82	234	SANDIA/DNA TESTS
▲	WELDED AGGLOMERATE	60	275	SANDIA TEST NO. 120-77
●	SANDSTONE	37	489	SANDIA TEST NO. 120-112
■	SANDSTONE	32	408	SANDIA TEST NO. 120-103
▼	GRANITE	32	462	SANDIA TEST NO. 120-106

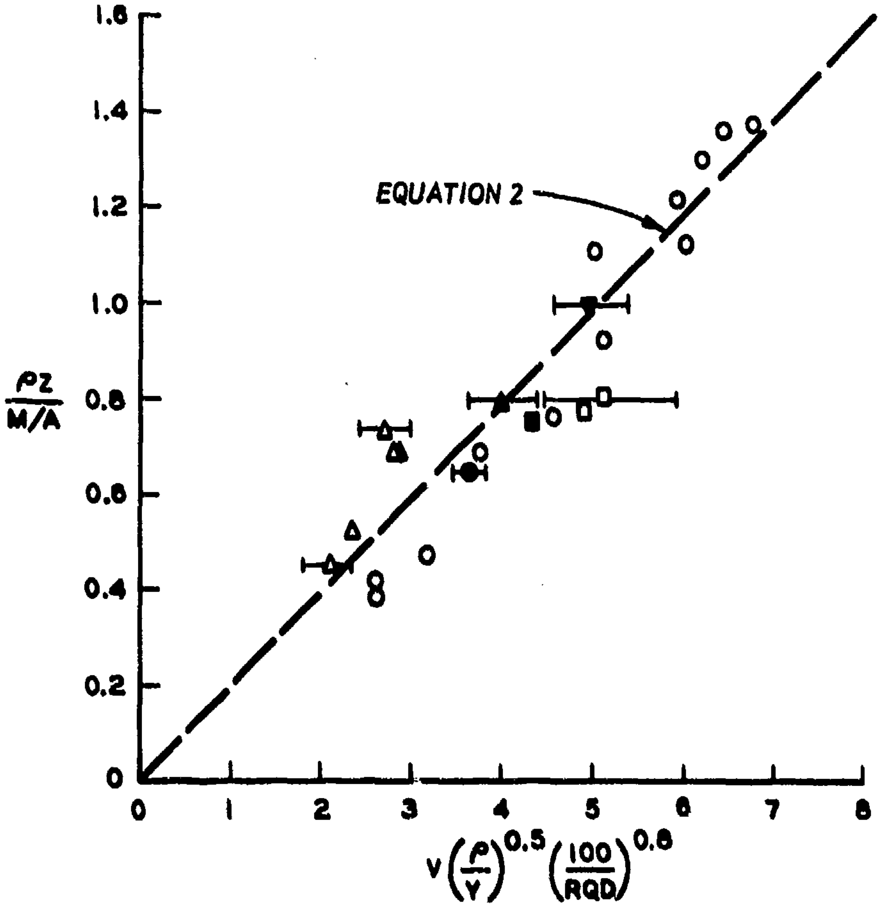

Figure 1. Data base for Equation 2

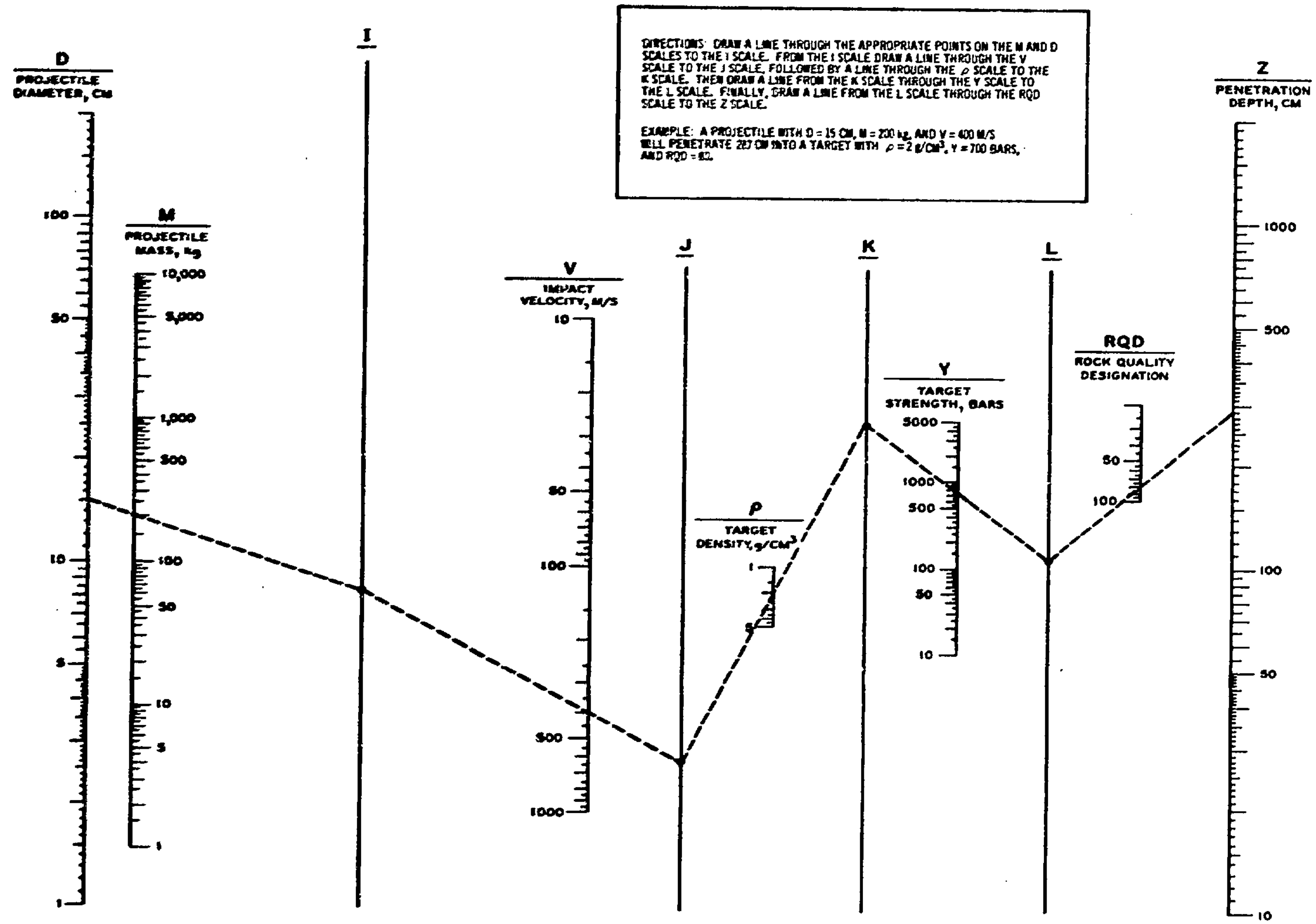

Figure 2. Nomogram for rock penetration (Equation 3)

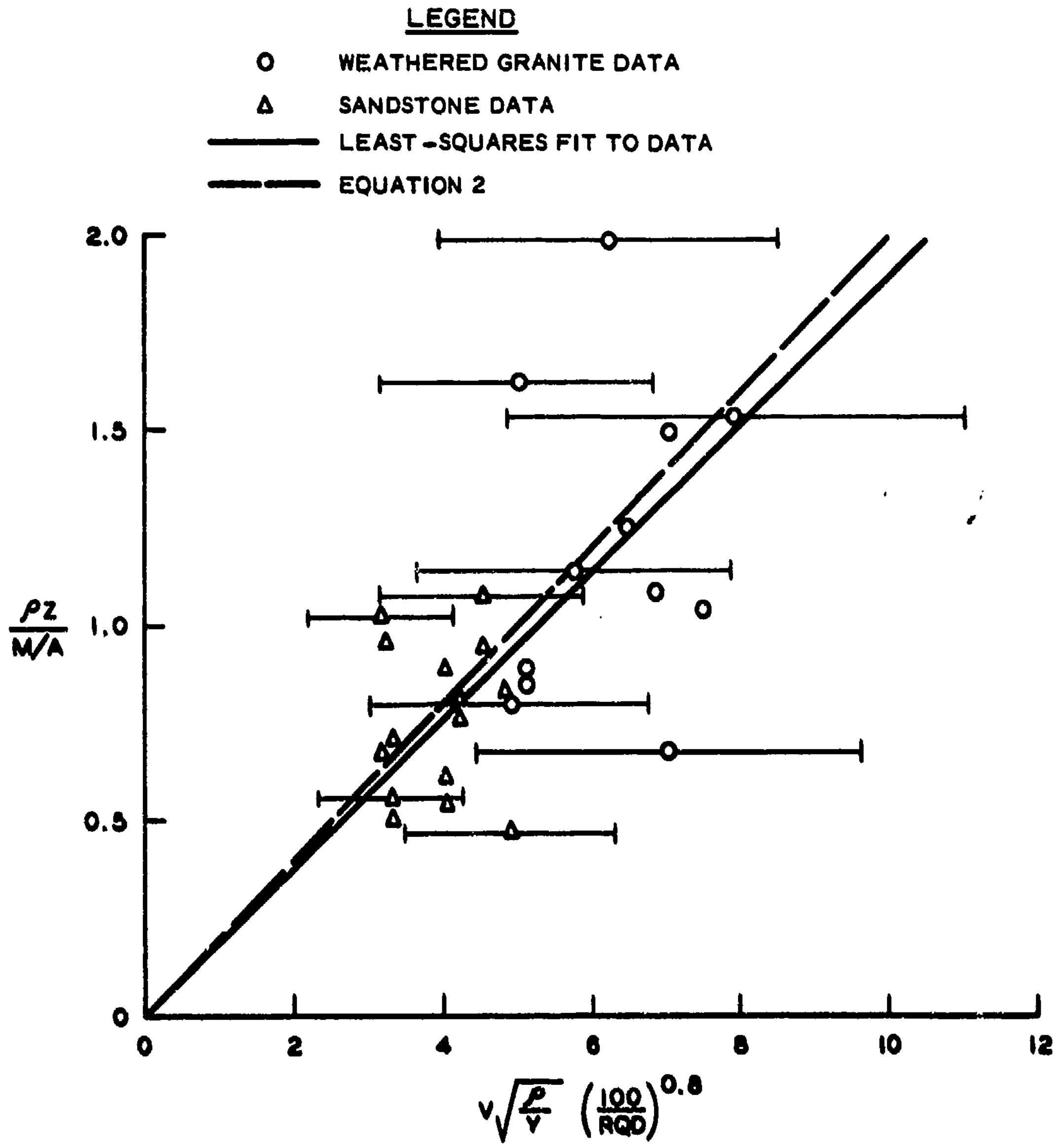

Figure 3. Comparison of Equation 2 with bomb penetration data

Appendix A: Estimating Rock Properties

Rock target descriptions often fail to include density, strength, or RQD measurements. Nevertheless, if geologic descriptions are available, it is possible to estimate these properties from Tables A1 through A3 (References 4, 5, and 6). The estimated properties can be used in Equations 2 and 3, or in the nomogram (Figure 2), to make <u>rough</u> calculations of penetration depth.

TABLE A1 ROCK QUALITY DESIGNATION

RQD, %	Rock Quality
0-25	Very Poor
25-50	Poor
50-75	Fair
75-90	Good
90-100	Excellent

TABLE A2 ENGINEERING CLASSIFICATION FOR INTACT ROCK

Class	Description	Compressive Strength bars
A	Very High Strength	Over 2200
B	High Strength	1100-2200
C	Medium Strength	550-1100
D	Low Strength	275-550
E	Very Low Strength	Less than 275

TABLE A3 COMMON INTACT ROCK DESCRIPTIONS

Rock Types	Typical Density g/cm^3	Strength Range bars
Soft Shale (clay shales, poorly cemented silty or sandy shales)	2.3	14-140
Tuff (nonwelded)	1.9	14-210
Sandstone (large grain, poorly cemented)	2.0	70-210
Sandstone (fine to medium grain)	2.1	140-500
Sandstone (very fine to medium grain, massive, well cemented)	2.3	400-1100
Shale (hard, tough)	2.3	140-800
Limestone (coarse, porous)	2.3	400-850
Limestone (fine grain, dense, massive)	2.6	700-1400
Basalt (vesicular, glassy)	2.6	550-1000
Basalt (massive)	2.9	>1400
Quartzite	2.6	>1400
Granite (coarse grain, altered)	2.6	550-1100
Granite (competent, fine to medium grain)	2.6	1000-1900
Dolomite	2.5	700-1400

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Bernard, Robert S
  Empirical analysis of projectile penetration in rock / by Robert S. Bernard. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1977.
  22 p. : ill. ; 27 cm. (Miscellaneous paper - U. S. Army Engineer Waterways Experiment Station ; S-77-16)
  Prepared for Defense Nuclear Agency, Washington, D. C., under Subtask Y99QAXSB211, "Penetration," Work Unit 14, "Technical Penetration Developments."
  References: p. 10.

1. Empirical method. 2. Penetration tests. 3. Projectiles. 4. Rock masses. I. Defense Nuclear Agency. II. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Miscellaneous paper ; S-77-16.
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